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Single and Dual Physical Link Failures Stability Effect on Degree Three WDM Networks

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Abstract— **This paper studies the effects of Single and Dual physical link failures to the stability of WDM networks when deployed as regular 3-degree structures. The failure impact on the source-destination pair connections is evaluated for the different topology scenarios. In this way it is possible to provide an overview of the failure effects and their relation to network metrics such as availability or cost. The results quantify how much the different network interconnection designs are affected by Single and Dual Physical link failures. The case study treats a realistic scenario, the interconnection of the NSFNET topology nodes. The main conclusions show that, when networks are designed under the same conditions, there is a linear relation between average downtime and ratio of connections affected by failures. Moreover, the most expensive optimized topologies to deploy provide higher availability.**

Keywords- Availability, Single and Dual Physical Link Failures, Regular Topologies.

I. INTRODUCTION

Long-haul optical backbone networks utilizing Wavelength Division Multiplexing (WDM) are designed to distribute huge loads of traffic across countries or even continents. Due to the huge capacity supported, these types of networks are required to provide high availability that for carrier grade networks can be as high as 99,999 % [1]. However, it is inevitable that link failures occur and these failures affect the overall network availability. To minimize the effect of link failures on network availability it is important to appropriately design these networks to support protection/restoration mechanisms in order to become fault tolerant. Optical networks are usually designed to offer survivability against single link failures with minimum additional capacity, while survivability in case of dual link failures is also considered but not as extensively. Shared risk link groups (SRLGs) [2] and network maintenance [3] are two common reasons that may lead to a dual link failure or an equivalent situation. In this context the impact of dual failures in the overall network performance has to be studied, as it can be of particular importance for networks requiring high degree of availability [4], [5], [6].

For this work, it is assumed that the probability of failure of links is directly proportional to their length implying that wide area are more likely to experience failures compared to networks that are more constrained in terms of physical distance [7]. Therefore, it is important to consider how the network is affected when failures occur, how the network reacts to these failures through protection/restoration mechanisms, how the overall network performance is affected while in the protection/restored status and how long the repairing time takes before the network re-establishes its working status.

It is well known that availability figures of a network design indicate the probability of losing connectivity between any two end-points of the network [8]. However, to the best of the authors' knowledge the effect of link failures over the established network connections has not been evaluated in detail and statistically analyzed to date. Thus, the main contribution and novelty of this work is to study and quantify the effect that single and dual link failures have in a realistic network scenario. These are various network topologies including regular 3-degree and 3-connected structures and the practical case of the NSEFNET topology. However node failures are not covered and left for further research.

In this context we define for the first time *Stability* as a metric to quantify to which extend the network is affected by the physical failure of one/various network elements. This metric will allow us to illustrate how the network graph is modified by the occurrence(s) of failures and to compare the consequences on different topologies with similar characteristics. This concept is closely related to *edge betweenness centrality* which quantifies the appearance of an edge in the shortest distance between vertices in a graph [9].

The methodology proposed to study the newly introduced concept of *Stability* consists of systematically removing one link to simulate the case of single failure (or a pair of links to simulate the case of dual failure) at a time to visualize the effect on the graph and all established connections. All links (and combinations of links for dual failures) are examined for the evaluation. These concepts are also applied on a case study of the practical NSFNET network topology [10].

The rest of this paper is structured as follows. Section 2 provides a brief summary of the previous results of [10] and covers some important definitions. Section 3 defines the methodology followed for the analysis. Section 4 presents the case study and results. Finally, Section 5 presents the conclusions of the work.

II. BACKGROUND

As mentioned in Section 1, the input of our study is taken from our previous work reported in [10]. This work involved the use of three different 3-degree topologies in order to physically interconnect the 16 NSFNET nodes as a WDM network system. Two different objective functions were used, availability as well as capital and deployment expenditure minimization using a specially developed Genetic Algorithm. So more specifically, the resulting topologies in [10] are taken as input to this study; these results include the collection of links and paths obtained at the design stage where two different routing schemes were used Minimum-Length and Hop Count. Also, two and three disjoint paths for each connection request were considered in order to study the effect of protection in the networks under study and the specific benefits of regular 3-degree interconnection designs. In addition to the practical NSFNET interconnection (Figure 1), Double Ring (DR), Chordal Ring (16,5) (CR(16,5)) and Chordal Ring (16,7) (CR(16,7)) topologies were studied (Figure 2). More detailed information on these topologies can be found at [11].

Table I, summarizes the characteristics of the interconnection results reported in [10] depending on the network properties (routing scheme, optimization and number of disjoint paths). The given cost for each of these topologies and cases covers trenching, spans and switching equipment expenses, 1 cost unit is the cost of a single wavelength. The availability (here presented as downtime) is determined considering line, amplifier and switch availability figures. Table I also provides a summary of the topologies and the corresponding parameters that are in detail examined in Section 4 and are indicated on the graphs included in the same section.

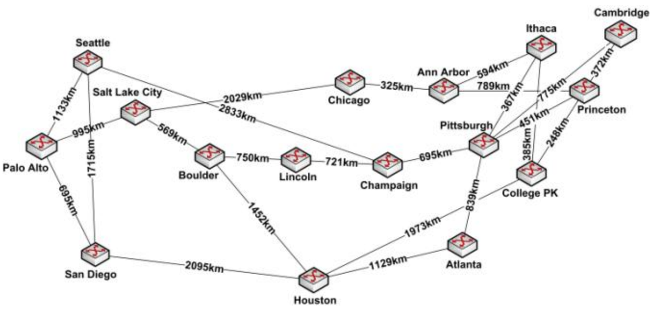

Figure 1. NSFNET interconnection

III. METHODOLOGY

As introduced in Section 1, the goal of this work is to determine the effect of single and dual link failures on the previously designed interconnection graphs for the 16 NSFNET nodes in [10] as regular 3-degree topologies and also on conventional NSFENT interconnection. These graphs correspond to the solutions when optimizing the physical interconnection of the nodes following a Double Ring and two types of Chordal Rings when the objective function is maximization of availability or minimization of capital and deployment expenditure.

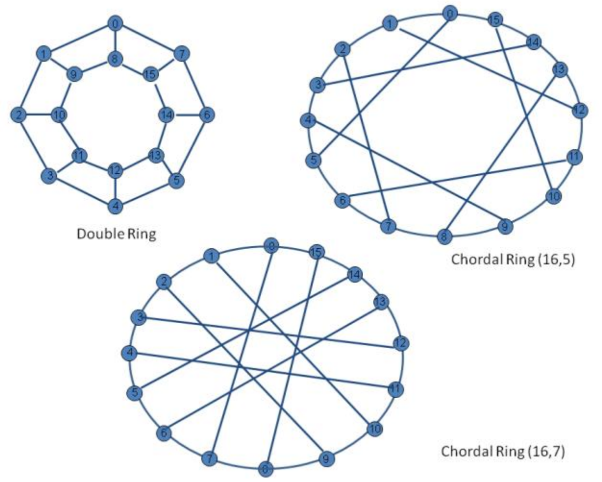

Figure 2. 3-degree topologies

Table I. Input topologies parameters.

Top.	Routing	Optimization	2 Disjoint Paths		
			Cost (cost units)	**Downtime, min/year**	**Figs.**
NFSNET	HC	None	24.301.142	1.872	5,7,8
	ML	None	24.297.502	1.844	5,7,8
DR	HC	Cost	24.226.411	1.853	5,7,8
		Avail.	24.226.411	1.853	5,7,8
	ML	Cost	24.222.871	1.828	5,7,8
		Avail.	25.672.133	1.818	5,7,8
CR(16:5)	HC	Cost	29.382.401	1.803	5,7,8
		Avail.	29.627.846	1.791	5,7,8
	ML	Cost	29.378.661	1.785	5,7,8
		Avail.	29.617.126	1.760	5,7,8
CR(16:7)	HC	Cost	25.775.367	1.879	5,7,8
		Avail.	26.593.057	1.835	5,7,8
	ML	Cost	25.774.767	1.872	5,7,8
		Avail.	27.071.516	1.800	5,7,8
Top.	**Routing**	**Optimization**	**3 Disjoint Paths**		
			Cost (cost units)	**Downtime, min/year**	**Figs.**
NFSNET	HC	None	24.540.282	0.859	-
	ML	None	24.540.182	0.848	-
DR	HC	Cost	24.721.471	0.00502	6,7,8
		Avail.	26.122.993	0.00490	6,7,8
	ML	Cost	24.715.671	0.00500	6,7,8
		Avail.	26.139.493	0.00493	6,7,8
CR(16:5)	HC	Cost	29.789.421	0.00453	6,7,8
		Avail.	30.013.006	0.00449	6,7,8
	ML	Cost	29.792.321	0.00454	6,7,8
		Avail.	30.033.306	0.00451	6,7,8
CR(16:7)	HC	Cost	26.257.388	0.00499	6,7,8
		Avail.	27.134.961	0.00479	6,7,8
	ML	Cost	26.252.787	0.00500	6,7,8
		Avail.	26.655.196	0.00476	6,7,8

Hence the data used for this work consists of the set of links and paths given as solutions in the following cases, being 32 cases in total:

- Type of routing: Hop-Count (MH) and Minimum-Length (ML).
- Number of disjoint paths (k): 2 and 3, k for the rest of the document.
- Deployed topologies: DR, CR (16,5), CR (16,7) and NSFNET, all 24 links ($L=24$) and 16 nodes, $N=16$.
- Type of optimization: Availability as well as capital and deployment expenditure.
- Dimensioning parameters: 16 wavelengths per fiber, 10Gbs per wavelength and maximum switch size 128X128.

The purpose of this work is to quantify the effect of physical link failures on these network interconnection cases. A single failure situation is referred to the time when there is one and only one link unavailable in the network. A dual failure situation is referred to the time when there are two and only two simultaneous link failures.

The procedure to study this effect is to systematically remove one link (single failure case) or link pairs (dual failure case) at a time and evaluate for each connection if the corresponding path has been affected. Throughout this work, each connection between a source and destination pair is considered as the set of working and protection paths. Hence, the connection of a source-destination (*s-d*) pair is defined as *affected* ($Af^{i}_{s\text{-}d}=1$) if the failure $link_i$ belongs to any of its k paths, formally defined in Eq. (1a). For the dual failure case the concept is similar for $link\_pair_{i,j}$ and $Af^{i,j}_{s\text{-}d}$, Eq. (1b).

$$Af^{i}_{s-d} = \begin{cases} 1 & \Rightarrow link_i \in Paths\,(s,d) \\ 0 & \Rightarrow link_i \notin Paths\,(s,d) \end{cases} \qquad \text{(a)}$$

$$Af^{i,j}_{s-d} = \begin{cases} 1 & \Rightarrow link_i \vee link_j \in Paths\,(s,d) \\ 0 & \Rightarrow link_i \wedge link_j \notin Paths\,(s,d) \end{cases} \qquad \text{(b) (1)}$$

For the rest of the document the connection of a source-destination pair is simply referred to as *connection.*

By applying this procedure to all possible link failures (single failure) and combination of two failures (dual failure) and evaluating all possible connections at the same time, all possible cases are covered. This evaluation leads to what we call *Stability analysis*.

More specifically we define *Stability* as a metric with the aim to quantify physical link failures consequences on the network connectivity in terms of ratio of affected connections. The *Stability* under failure of $link_i$ (S_i) is defined as the ratio of affected connections by this failure over the total number of existing connections. In our specific case all-to-all connections are assumed, N·(N-1). It is formally defined in Eq. (2a) for S_i and, similarly computed, the dual failure case ($S_{i,j}$) for $link\_pair_{i,j}$ is defined in Eq. (2b):

$$S_i = \frac{1}{N\cdot(N-1)}\sum Af^{i}_{s-d} \quad \forall\ s,d\ \in\ N \quad \text{(a)}$$

$$S_{i,j} = \frac{1}{N\cdot(N-1)}\sum Af^{i,j}_{s-d} \quad \forall\ s,d\ \in\ N \quad \text{(b) (2)}$$

The overall Stability (S_T) is calculated as the weighted average of all the contributions (all possible failures). The physical link failure probability is directly proportional to its length i.e. the longer the link the higher the probability of suffering a line cut. Thus, the contribution to the average result should be weighted in accordance to each specific link's length.

The weight given to a S_i of $link_i$ in the case of Single failure is given by Eq. (3a) being L_T the network's total length. The weight given to a $link\_pair_{i,j}$ failure effect in the case of Dual failure is given by Eq. (3b) being L_T*'* the sum of the length of all the possible link pairs multiplication, $L\cdot(L-1)$ pairs.

$$w_i = \frac{L_i}{L_T} \ \text{(a)} \qquad\qquad w_{i,j} = \frac{L_i \cdot L_j}{L_T\,'} \ \text{(b)} \quad (3)$$

The overall stability effect for the Single failure case (S^{s}_{T}) is calculated as described in Eq. (4a) and S^{d}_{T} for the dual failure case in Eq. (4b). The lower these values are the least effect failures will cause to the network performance.

$$S^{s}_{T} = \frac{1}{L}\sum_{i=1}^{L} w_i \cdot S_i \quad \text{(a)}$$

$$S^{d}_{T} = \frac{1}{L\cdot(L-1)}\sum_{i=1}^{L}\sum_{j=1}^{L} w_{i,j}\cdot S_{ij} \quad \forall\ i \neq j\ \text{(b)} \quad (4)$$

Furthermore, the number of remaining paths under failure conditions can be similarly quantified.

Let Rp^{i}_{m} be the number of connections with m paths remaining under failure of $link_i$. Then, the weighted average of the connections with m remaining paths at a single failure situation is given by Eq. (5a). The case of Dual failures follows the same idea being $Rp^{i,j}_{m}$ the number of connections with m remaining paths under the failure of $link\_pair_{i,j}$.

$$\overline{Rp_m}^{\,s} = \frac{1}{L}\sum_{i=1}^{L} w_i \cdot Rp^{i}_{m} \quad \text{(a)}$$

$$\overline{Rp_m}^{\,d} = \frac{1}{L\cdot(L-1)}\sum_{i=1}^{L}\sum_{j=1}^{L} w_{i,j}\cdot Rp^{i,j}_{m} \quad \forall\ i \neq j\ \text{(b)} \quad (5)$$

Finally it is possible to conclude that when the remaining paths $m=k$ for a connection under failure of $link_i$, then the connection is **unaffected** by failure $link_i$. Applying this concept to all the possible combinations, it is possible to define Eq. (6) for the single failure case, and similarly for the Dual failure case (Not displayed).

$$\overline{Rpk}^{s} = 1 - S^{s}{}_{T} \text{ (a)} \qquad \sum_{m=0}^{k-1} \overline{Rpm}^{s} = S^{s}{}_{T} \text{ (b)} \quad (6)$$

IV. CASE STUDY

This Section presents the failure analysis case study, as described in Section 3, over the mentioned interconnection topologies for the 16 NFSNET nodes. For Section 4.1 the results displayed in the graphs correspond to the 13 of the resulting interconnections from [10] (12 regular + NSFNET), which correspond to the optimized physical interconnection of the nodes in terms of availability and Sections 4.2 and 4.3 also include the interconnections optimized in terms of capital and deployment expenditure, 25 in total (24 regular + NSFNET).

The NSFNET topology is always the same but it is evaluated under the different routing conditions. However for the rest of the topologies, the interconnection varies depending on the routing and optimization criteria. Refer to Table I in Section 2 for the summary of the sample contribution to each of the Figures.

A. *Single and Dual failure effect*

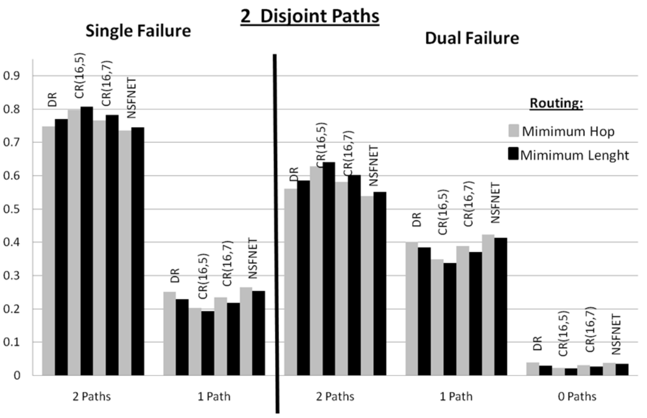

Figure 3. Two disjoint paths

Fig. 3 illustrates the results of the failure effect when the networks are designed to provide **two disjoint paths** (k=2) for the different topologies and single (left hand side of the chart) and dual failure (right hand side of the chart) scenarios. The displayed results correspond to the ratio of connections with 2, 1 or 0 remaining available paths under the failure conditions, $\overline{Rpm}^{s}$ and $\overline{Rpm}^{d}$ for 0≤m≤k.

In the case of Single failure, between 74-80% of the connections remain unaffected among all the topologies, while topology CR(16,5) appears to be the best performing one. In relation with the routing scheme, the Minimum-Length option shows a slightly lower impact than Hop-Count routing. In the Dual failure case, the results corresponding to the different topologies under consideration follow a similar pattern as that for the single failure. Concerning loss of connectivity, when dual failures occur between 2.1-3.8% of the connections will have all their paths affected causing loss of connectivity. In general, when providing two disjoint paths the highest ratio of affected connections corresponds to the NSFNET topology but closely followed by the DR.

In general the reason for deploying regular 3-degree topologies is that they are able to provide three disjoint paths regardless of the source and destination nodes of the connection requests. Hence, Fig. 4 presents the Stability effect over the studied topologies when designed to provide three disjoint paths. In case of single failures (left hand side of the chart), the benefit of the CR(16,5) is significant compared to the rest of the options. On the other hand, under these circumstances, for the NSFNET the failure effect is higher, more than 10% of the connections will be unprotected during this period, with only 1 path remaining. In the dual failure case (right hand side of the chart), the same pattern is followed and only the NSFNET will suffer loss of connectivity.

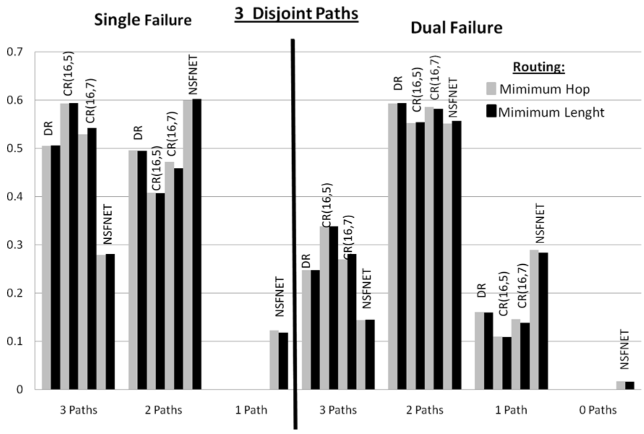

Figure 4. Three disjoint paths

As a conclusion, the real benefit of the 3-degree topologies in failure situations comes when the networks are designed to provide three disjoint paths. In this case, a network with more fair nodal degree distribution can provide noticeably better performance for working as well as failure situations and with similar cost to that of NSFNET (DR case), the cost for deploying each of the topologies varies between 24,3k and 24,7k depending on the case. Refer to Table I for the cost and ideal values of the topologies. Furthermore, this performance can be improved (~10%) by selecting the best performing 3-degree topology but with additional cost (CR(16,5) case). The cost of deploying a CR(16,5) varies between 29,3k and 30k depending on the case.

B. Downtime – Stability relation

The following results present the relation obtained between the average **downtime,** input from [10]**,** and **stability** ratio of the different network interconnections under Single (S^s_T) and Dual Failures (S^d_T). The displayed samples in Figs. 5 and 6 correspond to the 25 topologies referred to at the beginning of this Section. For Fig. 6 the results of NSFNET are omitted due to the fact that for NSFNET it was impossible to offer three disjoint paths between all the pairs of nodes.

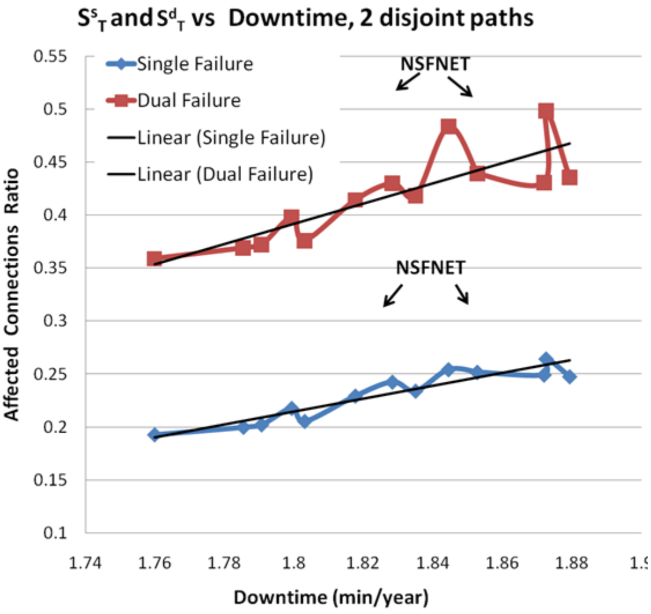

Figure 5. Stability vs. Downtime, two disjoint paths.

Figs. 5 and 6 illustrate the linear relation between **downtime** and **Stability** (S_T values). The identified patterns lead to the conclusion that when comparing different topologies supporting the same level of connectivity and the same constant disjoint paths, the lower the availability, the higher the Stability S_T in failure situations. The slope of this linear relation will depend on the specific availability numerical values used for the evaluation.

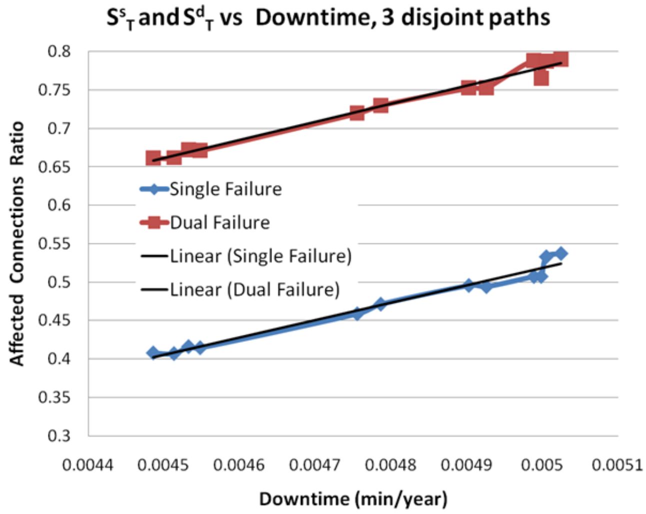

Figure 6. Stability vs. Downtime, three disjoint paths.

The two highlighted samples corresponding to the NSFNET results in Fig. 5 show a small upper deviation from the linear relation trend line in the case of double failures which becomes much lower in the single Failure case. This clearly highlights the consequences of an uneven nodal degree in the relation *downtime-*S_T*.*

The study of how this relation scales with the connectivity factor, number of nodes or nodal degree might be an interesting point to focus on for future studies.

C. Failure length - Stability relation

The following results illustrate the relation between the **average failure length** and **Stability** S_T when single and dual failures occur under two and three disjoint paths scenarios. In the case of Dual Failures the average length corresponds to the average sum of all the combinations of two failure links. The samples displayed in Figs. 7 and 8 correspond to the same cases as in Section 4.2 and, similarly, the results of NSFNET are omitted for the three disjoint paths samples due to the fact that it is impossible to offer three disjoint paths between all the pairs of nodes in the NSFNET case. Also the samples can be identified from Table in Section 2.

In this case the length of the network is directly related to the average failure length. The affected connections ratio is inversely proportional to the failure length. This effect is related to the specific topologies and their graph characteristics.

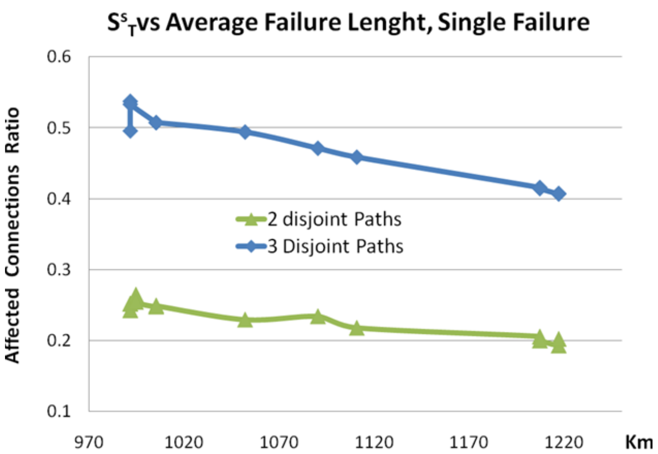

Figure 7. Stability vs. Avg. Failure Length, Single Failure.

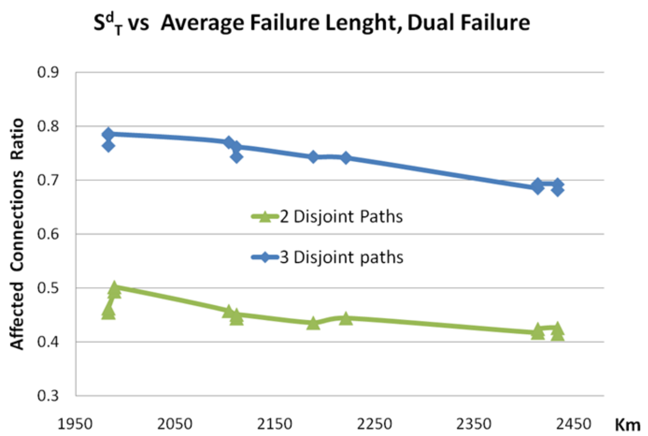

Figure 8 Stability vs. Avg. Failure Length, Dual Failure.

Topologies (optimized) requiring longer links to be deployed provide shorter physical length and hop distance paths. These two aspects are directly related to the connection availability and therefore it can be clearly identified that longer links do not strictly have a higher effect on the network stability under failure conditions. In fact, under our specific practical scenario the effect is the opposite. As observed, in this specific scenario, when different topologies are optimized (availability or cost wise) and they provide the same connectivity level, the longer the network, the lower the Stability effect S_T is in failure situations and therefore, failures cause less damage to the performance.

V. CONCLUSION

This paper has focused on the stability effect analysis in WDM optical networks under single and dual failures. In order to further study the failure support properties of 3-degree topologies and the traditional NSFNET the results from [10] were used to build the case study. These results consist of different sets of links and paths given as solutions of the optimization of the physical interconnection of the network following the mentioned 3-degree topologies, Double Ring and Chordal Rings. The optimization objective functions are maximization of availability or minimization of capital and deployment expenditure.

Following a systematic approach of removing a link at a time or pairs of links the effect of single and dual link failures has been analyzed considering all possible link (or pair of links) failures. The results lead to an overall conclusion that there is a linear relation between average downtime and ratio of connections affected by failures when networks are designed under the same conditions. In is shown that the most expensive optimized topologies to deploy provide higher availability due to the known fact that they allow shorter paths (in physical length and hop count). Hence these more expensive solutions are more stable in failure conditions, observing that as the average failure length increases the ratio of affected connections decreases. Furthermore, depending on the routing type, the affected connection ratio might slightly vary slightly under the same topology and conditions. The fact that it is not possible to provide 3 disjoint paths in the NSFNET clearly affects the global network stability under failure conditions, especially for the case of Dual failures.

As further work, the analysis of nodes failures effect over the different topologies could be interesting to extend this study.

REFERENCES

[1] M. To and P. Neusy , "Unavailability Analysis of Long-Haul Networks". IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, Vol. 12, No. 1, January 1994.

[2] E. Bouillet, G. Ellinas, J-F. Labourdette and R. Ramamurthy, "Path Routing in Mesh Optical Networks," John Wiley & Sons, Ltd.

[3] W. D. Grover, M. Clouqueur, T. Bach, "Quantifying and Managing the Influence of Maintenance Actions on the Survivability of Mesh-Restorable Networks," Proceedings of National Fiber Optic Engineers Conference 2001 (NFOEC 2001), vol. 3, pp. 1514-1525, July 2001.

[4] W. He and A. K. Somani, "Path-Based Protection for Surviving Double-Link Failures in Mesh-Restorable Optical Networks," in Proceedings of IEEE Globecom 2003, Dec. 1-5, 2003

[5] L. Guo, L. Li, J. Cao, H. Yu and X. Wei, "On Finding Feasible Solutions With Shared Backup Resources for Surviving Double-Link Failures in Path-Protected WDM Mesh Networks," Journal Of Lightwave Technology, Vol 25, No. 1, January 2007

[6] J. Doucette, M. Clouqueur and W. D. Grover, "On the availability and capacity requirements of shared backup path protected mesh networks," Optical Networks Magazine, November/December 2003.

[7] Wayne D. Grover, "Mesh-Based Survivable Networks, Options and Strategies for Optical, MPLS, SONET and ATM Network" Prentice Hall PTR, 1st edition (August 14, 2003).

[8] Ivan Rados, "Availability Analysis and Comparison of Different WDM Systems". Journal of Telecommunications and Information Technology. 1 (2007) , 2; 114-1-119-6

[9] L.C. Freeman. "A set of measures of centrality based on betweenness. Sociometry 40:35-4,1 1977

[10] J. M. Gutierrez, K. Katrinis, K Georgakilas, A. Tzanakaki, O. B. Madsen, "Increasing the cost-constrained availability of WDM Networks with Degree-3 Structured Topologies". ICTON 2010

[11] J.M. Pedersen, "Structural Quality of Service in Large-Scale Network". PhD Thesis. Control Department, Aalborg University, Denmark. April 2005.